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Influence of the Electron Seed Properties on the Discharge Characteristics of a Pseudospark (Preprint)

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Abstract

An investigation is put forth concerning the extent to which the pseudospark discharge characteristics are controlled by the mean injection velocity of the seed electrons when the bulk of the initial plasma generation occurs independently of the influence of the initial penetrating electric field from the anode-cathode voltage difference. The study is performed using the two-dimensional kinetic plasma simulation code OOPIC Pro. The discharge is seeded by injecting a current pulse for a period of one nanosecond along the axis from the hollow cavity back wall over a range of mean speeds corresponding to 100 to 900 V accelerations. It is shown that the mean seed injection energy strongly influences the rate of growth of the virtual anode with the neutral gas pressure and the magnitude of the peak electron current to the anode generated in the breakdown phase.

I. Introduction

The pseudospark[1-6] is a low pressure gas discharge comprised of hollow cathode and anode cavities each covered by an electrode with a hole in the center and is capable of producing a rapid current rise up to 10^{12} A/s [1] with current densities > 10^6 A/cm^2 [4].

The pseudospark operates on the left-hand-side of Paschen's curve, which shows the scaling of the breakdown voltage as a function of pd, where p is the gas pressure and d is the anode-cathode gap distance. Due to the special geometry of the pseudospark, the electric field distribution is non-uniform and time-dependent, resulting in a breakdown voltage that is shown to scale as a function of $p^2 d$ [7], although other scaling exponents have also been suggested [9]. Pseudospark discharges are operated just below the self-breakdown voltage and are externally triggered [8-12] by the injection of seed electrons into the hollow cathode cavity, which can be achieved electronically or by photo-emission. The optically-triggered method is usually referred to as the backlighted-thyratron (BLT). Experiments have shown that the number [8] of seed electrons needed to initiate a discharge is of the order of 10^9 to 10^{10}.

The physics of pseudospark operation can be complex and several characteristic phases have been identified by various authors. Although the nomenclature of such phases can be varied, it is generally agreed [13-15] that the discharge is characterized by space-charge build-up, followed by rapid ionization avalanche and electron beam formation, and finally a super-emissive state. The physical model for the latter phase (also called "super-dense glow") is not yet well understood, albeit likely to involve a self-sustained sputtering [16], and is not being modeled here; our attention is focused on the triggering and avalanche processes, which can be identified here as the (a) pre-breakdown and; b) breakdown phase. During the pre-breakdown phase electrons generated through ionization are accelerated to the anode leaving behind a region of net positive charge called the virtual anode. In the breakdown phase the plasma generation rate inside the virtual anode multiplies resulting in high plasma densities and the slow growth of the virtual anode. It is during this phase that an electron beam forms along the axis.

The effect of injecting a current pulse on the discharge breakdown characteristics in other configurations has received previous attention [17-20]. It is established [18-20] that when a current pulse is used to initiate breakdown the minimum voltage needed across the gap decreases. Cooley and Choueiri [19] have shown that this is due to the enhancement of the electric field due to the space charge generated by the current. Previous studies [17] of the pseudospark discharge have shown that, in general, the magnitude of the peak electron current grows as the mean seed injection energy increases, where the three mean seed velocities parallel to the cathode hole axis used were none, the energy corresponding to the ionization peak cross-section and fifteen times this value. It was shown that the increase in density is due to the ability of the seed electrons to generate a surplus plasma independent of the initial penetrating electric field from the anode-cathode voltage difference. These extra electrons act as an additional source enhancing the particle multiplication as the space charge distorted electric field grows upstream.

An investigation of the influence of the seed electron energy on the characteristics of the pseudospark discharge in the pre-breakdown and breakdown phases for a range of neutral gas pressures is presented. The pseudospark geometry is chosen such that the magnitude of the electric field from the anode-cathode gap is insufficient to promote electron impact ionization throughout most of the hollow cathode backspace. It is shown that the residence time of the initial electrons in the hollow cathode, which is determined by the mean seed injection velocity, modifies the early particle density and the delay time of the initial formation of an electric field due to the space charge sufficient to enhance ionization. This influences the rate of growth of the virtual anode with the gas pressure and the magnitude of the peak electron current. The results are discussed in section III. In section II a description of the physical model employed in the study and the code used to generate the simulations, OOPIC Pro, is presented.

II. The Model

The physical investigation is performed using two-dimensional electrostatic kinetic particle-in-cell simulations generated by OOPIC Pro [21]. The code accounts for Monte-Carlo collisions and ionization and features both electrostatic and electromagnetic field solvers. Additionally, both electron and ion impact secondary electrons from the surfaces are modeled.

The simulation parameters such as the cell-size, time-step and particle-weighting have been selected to minimize the impact of fluctuations and grid heating. Each parameter has been decreased to a point where successive reductions produce the same physical results and the largest values with consistent outcomes have been selected to minimize computing time.

The physical model framework and geometry is illustrated in Fig. 1. The model employs a fixed hollow cavity height Y_{max} = 50 mm, anode-cathode gap d = 5mm, depth D =25 mm, cathode thickness w = 3mm and hole height h = 4mm. A total of 1×10^{10} seed electrons are injected at the center of the hollow cavity's back wall over a period of one nanosecond. This interval of time is less than that required to form a discharge in the pre-breakdown stage. The seed electrons have a thermal spread of 2.5 eV and a mean velocity normal to the wall source corresponding to 100, 300, 500, 700 or 900 V accelerations. For a given mean injection velocity simulations are run over a range of neutral gas pressures extending from 0.1275 to 1.8 torr. Common to all simulations is the use of Argon gas, an anode voltage of 10 kV, a grounded cathode and the inclusion of secondary electrons due to both electron and ion impact. Electron impact ionization, exclusively, is accounted for.

III. Results And Discussion

Plots of the time to reach the peak electron current to the anode, t_p, (see Fig. 2) and its magnitude (see Fig. 3) versus the neutral gas pressure, P, reveals the extent to which the average seed injection velocity influences the discharge properties in the pre-breakdown and breakdown phases for the hollow cathode geometry and seed energies employed. The time taken to reach the peak electron current indicates the rate of growth of the virtual anode. The magnitude of the net positive charge density formed in the vicinity of the hollow cathode hole depends on the number of electrons and ions created, primarily through ionization, and the rate at which electrons leave this region for the anode. The number of secondary electrons due to both electron and ion impact in the study presented, is not significant enough to affect the discharge properties.

Under the situation modeled it is primarily the mean seed energy as opposed to the influence of the initial penetrating electric field due to the anode-cathode voltage difference that dominates the variation in the discharge properties with neutral gas pressure. For the hollow cathode dimensions employed the initial electric field due to the anode-cathode voltage difference penetrates only a few millimeters into the hollow cathode and therefore plasma creation through the rest of the region is dependent upon the seed properties. The range of mean injection energies utilized, 100 to 900 eV, ensure that the electrons are able to create a plasma as they traverse through the hollow cathode interior.

While the properties of the discharge in the pre-breakdown phase vary with the average electron seed injection energy information about the initial seed velocities is rapidly lost. A plasma is created as the electrons travel from the source towards the hole, losing their directed velocity through ionization energy losses and scattering. Since the seed injection period is less than the time taken for the electrons to travel through the hollow cathode, the faster electrons leave the region resulting in a pre-breakdown discharge characterized by its number density and net positive charge.

The peak electron current arriving at the anode rises with pressure and with the mean injection energy of the seed electrons as figure 3 demonstrates. As the injection velocity increases, the residence time of the seed electrons in the hollow cathode interior decreases, resulting in an earlier development of a net positive charge that is substantial enough to generate electric fields sufficient to enhance particle multiplication through ionization.

Plots of the time taken to reach the peak electron current at the anode, t_p, versus the pressure display a minimum in the curves (see figure 2). On the far left-hand-side both ionization energy losses and particle generation are at a minimum. The electrons with a relatively short residence time leave behind very little net positive charge resulting in a slow growth of the virtual anode. As the pressure increases on the left-hand-side the influence of the rise in particle generation dominates over the effect of a longer electron residence time resulting in a more rapid growth of the space charge distorted electric field. The rate of growth of the virtual anode decreases with increases in the particle generation. When the right-hand-side is reached, increases in electron residence time due to ionization energy losses give rise to a smaller net positive charge being left behind although the total particle generation is much larger. Now, the time taken to reach the peak current increases with the electron residence time.

On the left-hand-side of the t_p versus P curve the time increases without bound indicating the minimum neutral gas pressure required for the discharge to achieve breakdown. There are also limits in how far the neutral gas pressure can be increased on the right-hand side of the curve before the formation of a pseudospark discharge is inhibited. Substantial increases in the pressure results in the formation of a plasma primarily confined within the anode-cathode gap, as figure 4 illustrates. Upon leaving the source the electrons rapidly lose their mean velocity due to ionization energy losses. Plasma generation is dominated by the avalanche process that ensues after a few of these electrons arrive in the region where the initial penetrating electric field can re-accelerate them to ionizing energies.

Generally, the minimum in the t_p versus P curve shifts to higher pressures as the mean injection velocity increases except when the speed corresponds to a 100 V acceleration as is illustrated in figure 5. Due to the higher net speed of the initial electrons through the hollow cathode the pressure at which ionization energy losses result in a longer residence time such as to retard the growth of the net positive space charge increases.

The time spent in the pre-breakdown and breakdown phases decreases as the mean electron seed injection velocity increases as is shown in figure 6. The period of time at the minimum of the t_p versus P curve increases from 13.6 to 320 nanoseconds for the largest and smallest seed energies employed, respectively. The shorter residence time of the faster seed electrons results in an earlier and more rapid growth of a positive space charge region.

IV. Conclusions and Summary

If the bulk of the initial plasma generation by the seed electrons is independent of the influence of the initial penetrating electric field due to the anode-cathode voltage difference then the discharge properties in the pre-breakdown and breakdown phases are strongly influenced by the mean seed injection velocity.

Increases in the mean seed injection speed result in a shorter electron residence time, giving rise to an earlier and more rapid development of the net positive space charge and its corresponding electric field. This results in higher peak electron currents to the anode being developed in the breakdown phase and an increase in the gas pressure at which the virtual anode has its most rapid growth. There is an order of magnitude increase in the shortest time taken to reach the peak current, t_p, as the mean energy decreases from 900 to 100 eV.

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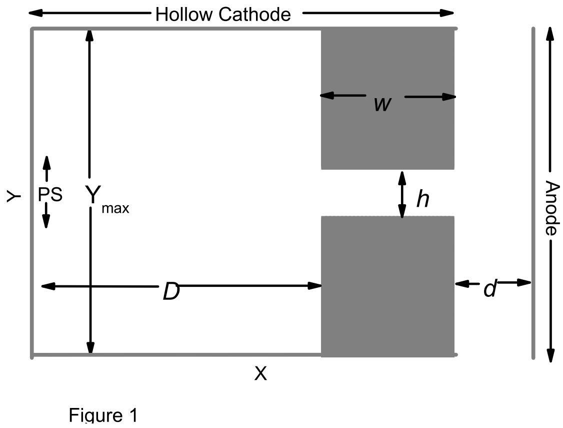

FIG. 1. The model setup, where PS indicates the electron seed injection location.

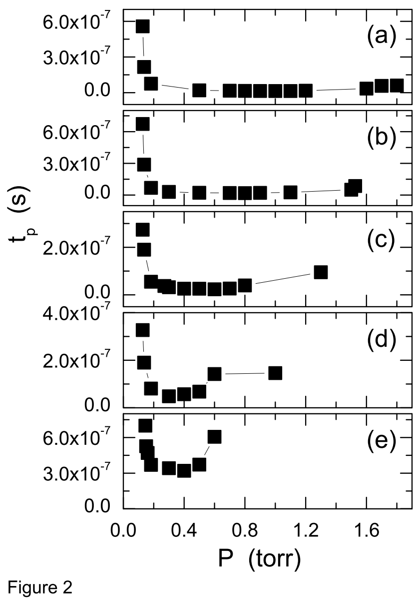

FIG. 2 The time taken to reach the electron peak current t_p versus the neutral gas pressure P for the following range of mean seed injection energies (a) 900, (b) 700, (c) 500, (d) 300 and (e) 100 eV.

Figure 3

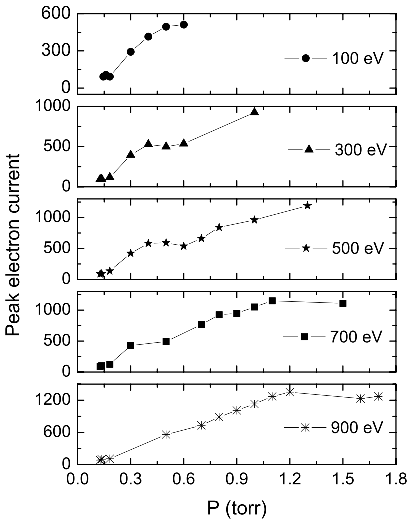

FIG. 3 The peak electron current arriving at the anode (A/m), where the value is per meter in the ignorable direction, versus the neutral gas pressure P for the indicated value of the mean seed injection energy.

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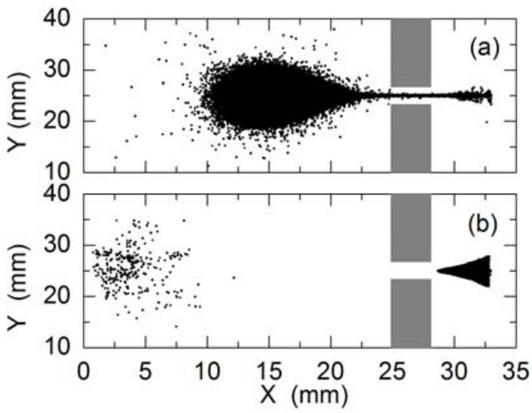

FIG. 4 Electron X-Y phase space at the time of the peak electron current where the mean seed injection energy is 500 eV and the neutral gas pressure is (a) 0.127 and (b) 1.5 torr.

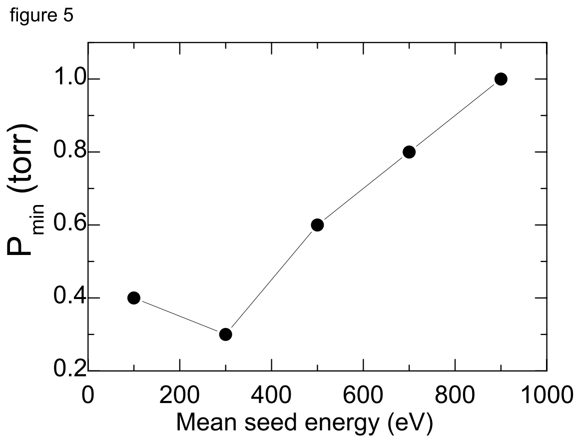

FIG. 5 The magnitude of the neutral gas pressure at the minimum of the t_p versus P curve, P_{min}, against the mean seed injection energy.

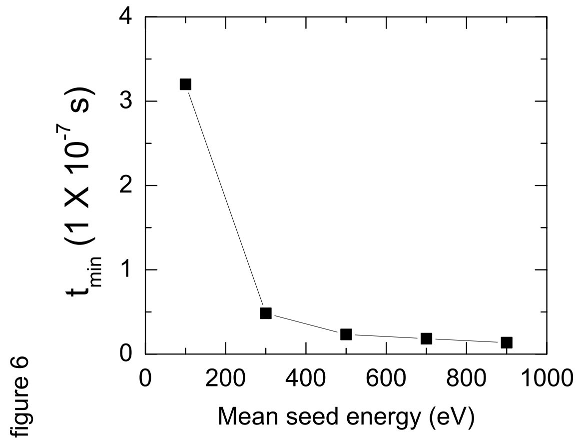

FIG. 6 The magnitude of the time to reach the electron peak current at the minimum of the t_p versus P curve, t_{min}, against the mean seed injection energy.